Rotating Exchange Flow

PI:
Daniel R. Ohlsen
Colorado Research Associates
3380 Mitchell Lane
Boulder, CO 80301
phone: 303-415-9701 fax: 303-415-9702 email: Daniel.Ohlsen@colorado.edu

Co-I:
John E. Hart
Program in Atmospheric and Oceanic Sciences
Campus Box 311
University of Colorado
Boulder, CO 80309-0311
phone: 303-492-8568 fax: 303-492-3524 email: hart@tack.colorado.edu

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LONG-TERM GOALS

Flow through ocean straits and channels helps set the water-mass properties of the larger basins at each end. The long-term goal of this research is an understanding of the roles that rotation and friction play in the transport and water-mass mixing of flows through oceanic straits, channels, and canyons.

OBJECTIVES

Ocean exchange flows that are wide or slow enough are subject to the Coriolis force owing to planetary rotation. Together with boundary and interfacial friction, the Coriolis force drives cross-channel, secondary circulations. Oceanic examples of channels in which observations have found the signature of the cross-channel circulations explored in this project include the exchange flows through the Vema and Faroe Bank channels. The short-term goals of this study were to understand the dynamics of these secondary circulations, particularly their influence on interfacial mixing in, and transport through, such straits.

APPROACH

Until recently, dynamical models that have been used to predict transport through straits and channels have been based primarily on inviscid, nonrotating hydraulics (Pratt, 1991 for a review). This theory could be sufficient for straits that are short and narrow with smoothly varying topography and no tidal time-dependence. When compared with observations however, these transport predictions generally overestimate the measured values. Some obvious additions to the nonrotating hydraulic formulation include rotation, friction, topography, interfacial mixing, along- and cross-channel density variations, and time-dependence. (See Bryden and Kinder, 1991 for references for each of these effects.) Various ocean channels and straits can have one or more of these factors give order-one variations in predicted transport. Whitehead (1989, 1998) has reviewed the various predictions and measurements through a number of both deep and shallow ocean straits.

In the present study we examined the effect that planetary rotation in combination with boundary friction and small-scale interfacial mixing had on transport and bulk interfacial mixing in exchange flow through

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straits. Both two-layer, hydraulically driven exchange and continuously stratified, thermally driven flows were studied with laboratory experiments. A 2-1/2 dimensional numerical model was also used to examine the two-layer case.

This year we concentrated on a laboratory set-up that consisted of two basins joined by a tube through which water of different salinities is exchanged. Salt is added to the basins at each end to adjust the density and therefore the hydraulic head, and the experiment is started by removing a dam blocking one tube end. In concept the experiments are much like those of Johnson and Ohlsen (1994) but much more quantitative. The whole apparatus sits on a rotating table to simulate planetary rotation. The Flared ends on the tapered tube help insure that the hydraulic control point in each layer is near the center of the tube length. A laser sheet projected across the tube cross-section allowed non-intrusive cross-channel density field measurements via the laser-induced fluorescence technique. These measurements were particularly useful for measuring interfacial mixing and cross-channel transport. A precision micro-CTD probe and high-resolution direct density measurements were used to measure salinity or density changes in the outer basins and thereby measure transport through the channel.

In the other laboratory experiment, a free-surface strait joined a warm and a cool basin. See the 1997 Annual Report for a description and results.

With the numerical model we computed all three components of velocity, the pressure, and the density (salinity or temperature) but in a 2-dimensional cross-channel plane. All downstream derivatives except the downstream pressure gradient are ignored. A finite-difference formulation was used so that the no-slip channel walls were easily included. The numerical flow was forced via the downstream pressure gradient. This model was a direct numerical simulation for laboratory scales in the y-z plane in that scales down to dissipation were resolved.

WORK COMPLETED

An extensive parameter space search with the both the numerical model and two-layer laboratory experiments found a simple empirical relation between the exchange rate and the hydraulic head, planetary rotation, and viscous input parameters. The numerical model was further verified by comparisons to the laboratory cross-channel density field measurements.

RESULTS

Planetary rotation reduces the transport in two-layer exchange flow through a strait. The inclusion of side-wall and interfacial friction and mixing gives a smaller (and improved) predicted transport than the inviscid theory unless rotational effects completely dominate the flow. The experiments verify the frictional and Coriolis dependence of the numerically predicted transport. In addition, the presence of even weak cross-channel circulations enhances the production of intermediate property fluid by mixing between the two layers. This intermediate fluid is directly advected away from the interface by the secondary circulation rather than just diffused by turbulent mixing as in the nonrotating case.

The most important result from this study is an improvement of the transport relation of Whitehead *et al.* (1974) for hydraulically-driven two-layer exchange flow. That model included rotation but neglected viscosity and interfacial mixing. Their predicted transport was reduced for larger rotation and was checked against laboratory experiments in a very short tube for which friction was small. The maximum transport in a two-layer hydraulic exchange is obtained when the interfacial Froude number is unity, i.e. when the velocity difference between the two layers is at the long-wave-speed limit. If the entire layer has this velocity then the maximal exchange is $Q_0 = HL\sqrt{g'H/2}$ where H is the layer depth, L the

channel width, g' the reduced gravity, $g' = g\Delta\rho/\bar{\rho}$, $\Delta\rho$ the layer density difference, and $\bar{\rho}$ the average density. In Whitehead *et al.* (1974) the nondimensional transport, Q/Q_0, depends only on L_R/L, the ratio of the Rossby radius to the channel width where $L_R = \sqrt{g'H}/f$ and f is the Coriolis parameter. Their nondimensional transport asymptotes to 0 for small L_R/L, is 0.5 at L_R/L 0.5 and asymptotes to 1 for large L_R/L where rotation becomes unimportant. Johnson and Ohlsen (1994) measured exchange transport through a rotating two-layer cylindrical tube geometry for which friction could not be neglected, and found much smaller transport than predicted by the inviscid theory.

Non-rotating exchange flow, i.e. simple two-layer shear flow, is limited by Kelvin-Helmholtz instability, interfacial mixing, and eventually overturning and breakdown of the interface. Anati *et al*. (1977) presented a simple argument for turbulent interfacial layers which gives $Q/Q_o = 1 - R_i F^2/2$ where R_i is the shear Richardson number (traditionally 1/4 at laminar breakdown) and F, the Froude number. Measurements of Ri in laboratory experiments, in the ocean, and in the atmospheric boundary layers have found R_i from ~0.2 to ~0.33 and therefore $0.83 < Q/Q_0 < 0.9$. Hence, at large L_R/L where rotation is weak, the transport will still be limited to less than the maximum by shear flow instabilities.

In our experiments and numerical model we bridge the gap between the two limiting cases of inviscid-rotating and viscous-nonrotating flow. In a series of numerical model runs and laboratory experiments we checked the dependence of Q/Q_0 on each of the parameters: g', f, ν, and Channel Length individually. The first result was that the transport, Q/Q_0, is proportional to log(g') and separately to log($1/f$) with the

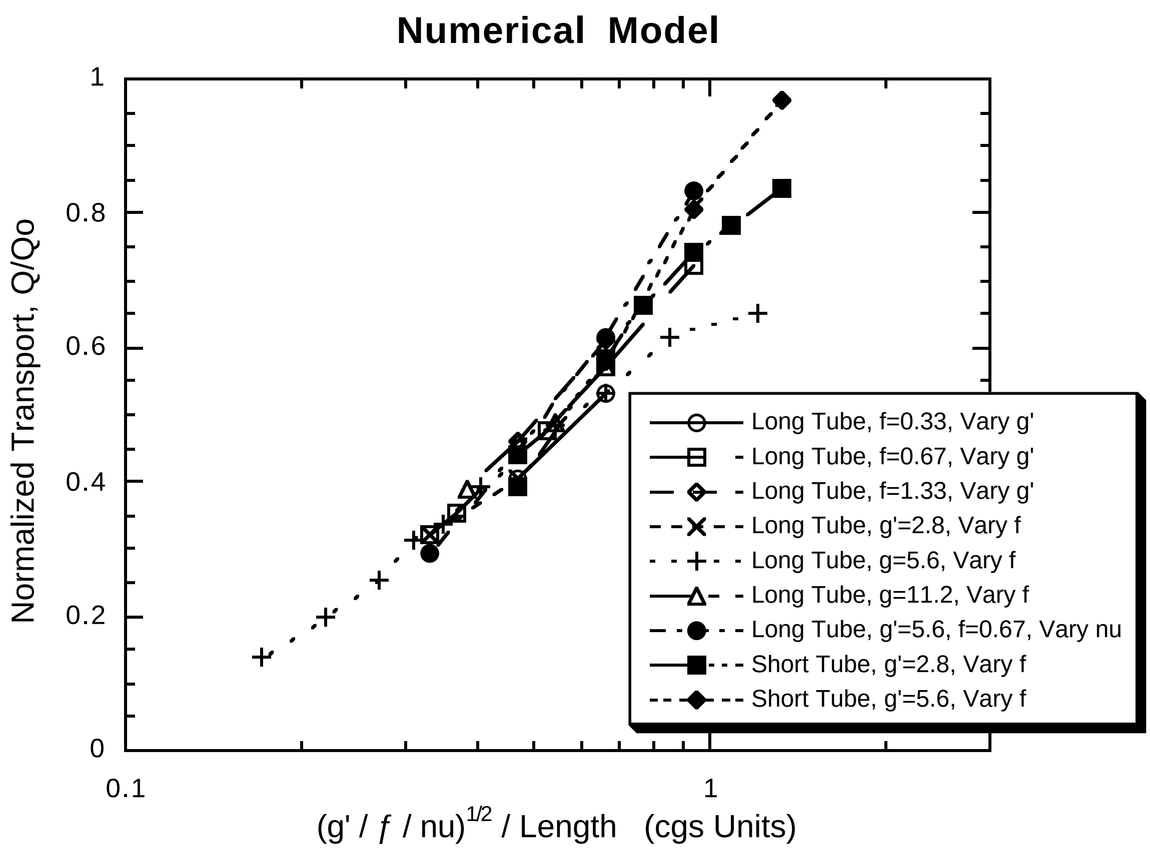

Figure 1. Transport calculated with numerical model with one parameter varied at a time. The parameters are dimensional and chosen to match the laboratory experiments.

same proportionality constant. This result is different from the Whitehead *et al*. (1977) dependence on L_R/L which is proportional to $\sqrt{g'}/f$. A summary of all the results for the numerical model runs is shown in Figure 1. All the results can be scaled to a single functional dependence on $\gamma = \sqrt{g'/f/\nu}/Length$. On the log-linear plot the data is nearly linear indicating an approximate logarithmic dependence on γ.

We were unable to derive a theoretical prediction for the transport dependence on this parameter. However, we checked this empirical numerical model result with the laboratory experiments. The results are shown in Figure 2. Again all the data collapse to a nearly logarithmic dependence on γ. At large γ, the laboratory transport is less than predicted by the model, most probably due to the model's neglect of down-stream mixing. In most of the parameter space, however, the 2-dimensional model captures most of the physics. In terms of non-dimensional parameters with which one could scale this result up to oceanic flows, γ could be written in terms of

$$\gamma = \frac{L_R \cdot H}{Length \cdot \sqrt{E_k}},$$

where E_k is the usual Ekman number, $E_k = \nu / f / H^2$. However it is certainly true that the transport must depend on the channel width as in Whitehead *et al*. (1974) for small enough Ekman number so there must also be an L dependence in γ. We did not vary L and did not derive the empirical dependence

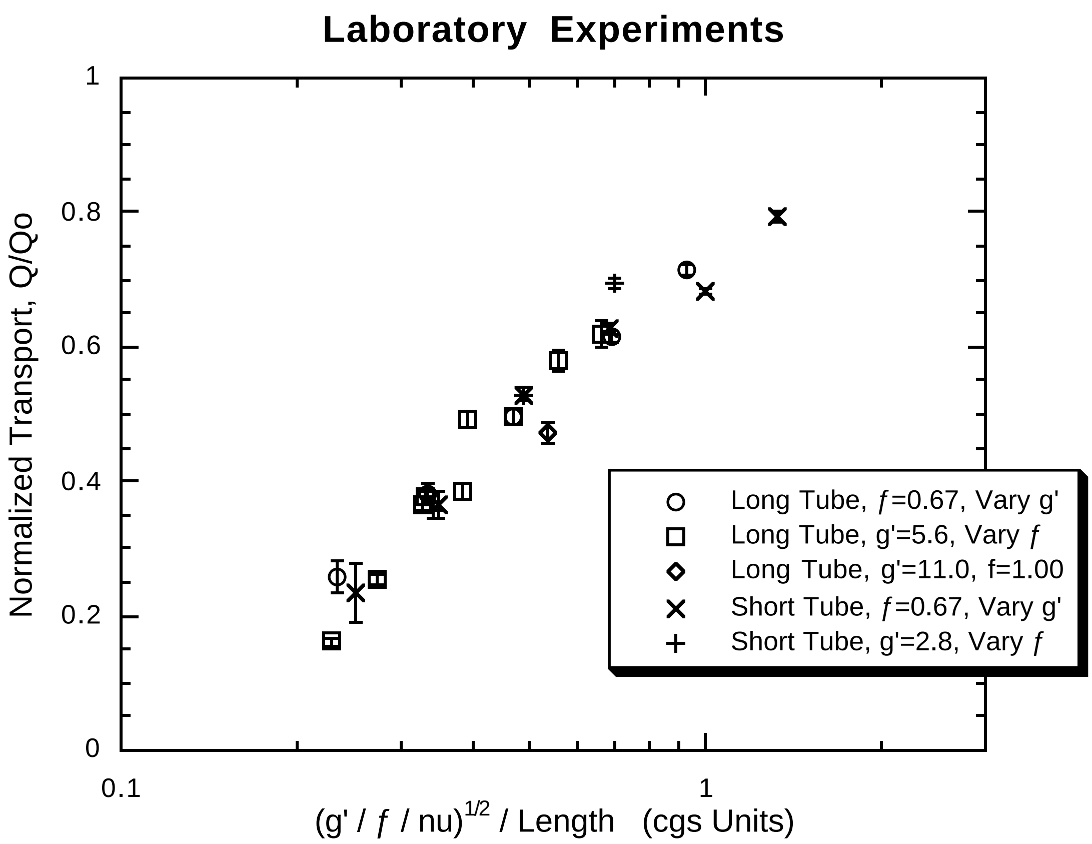

Figure 2. Transport and error bars measured in the laboratory experiments with one parameter varied at a time as in the numerical model. The channel is either 62 or 31 cm long and is a 3.9 cm x 3.9 cm square at the narrowest point.

The basic physical picture was outlined by Johnson and Ohlsen (1994) and Ohlsen (1996, 1997). The downstream flow is in approximate geostrophic balance except near the boundaries and at the interface between the two layers. There viscosity is important and Ekman layers form. The result is a two-cell cross-channel circulation in each layer. Along the interface, fluid mixes between the two layers and is then advected in the cross-channel circulation along the interface. This circulation separates before reaching the side-wall and the mixed fluid is directly injected into the bulk of the layer. This cross-channel circulation in both experiments and model thus increases the vertical distance that mixed fluid can travel compared to the non-rotating case (where the mixed fluid is trapped to the K-H unstable region). Both the experiments and model were run in the laminar flow regime. For larger, ocean-scale flows we expect that the interface could be turbulent with more mixing, especially in the down-stream direction. An eddy viscosity might be able to scale γ to still get a transport calculation. Or if measurements are available, a bulk eddy viscosity could be derived by working backward from the transport measurement.

IMPACTS/APPLICATIONS

The increased vertical mixing which planetary rotation forces in exchange flows is important to boundary condition parameterizations in numerical models of basin or global scales. The thermally-driven experiments expand the oceanic applicability of this study, since these generalize the two-layer version to continuous stratification. In addition, they explicitly target the entire linked basin/strait system, including the convecting basin, the exchange flow through the strait, and the mixing and entrainment of the convecting fluid as it enters and exits the strait.

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